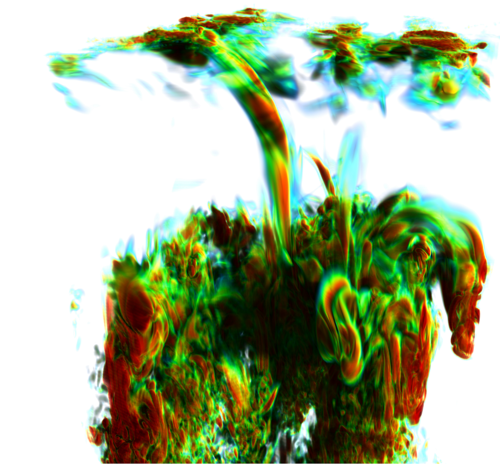
Realistic Modeling of Interaction of Quiet-Sun Magnetic Fields with the Chromosphere



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High-resolution observations and 3D MHD simulations reveal intense interaction between the convection zone dynamics and the solar atmosphere on subarcsecond scales. To investigate processes of the dynamical coupling and energy exchange between the subsurface layers and the chromosphere we perform 3D radiative MHD modeling for a computational domain that includes the upper convection zone and the chromosphere, and investigate the structure and dynamics for different intensity of the photospheric magnetic flux. For comparison with observations, the simulation models have been used to calculate synthetic Stokes profiles of various spectral lines. The results show intense energy exchange through small-scale magnetized vortex tubes rooted below the photosphere, which provide extra heating of the chromosphere, initiate shock waves, and small-scale eruptions.

'StellarBox' code (A. Wray)

- ✓ 3D rectangular geometry
- ✓ Fully conservative compressible MHD
- ✓ Fully coupled radiation solver:
  - LTE using 4 opacity-distribution-function bins
  - Ray-tracing transport by Feautrier method
  - 18 ray (2 vertical, 16 slanted) angular quadrature
- ✓ Non-ideal (tabular) EOS
- ✓ 4th order Padé spatial derivatives
- ✓ 4th order Runge-Kutta in time
- ✓ LES-Eddy Simulation options (turbulence models):
  - Compressible Dynamic Smagorinsky model (Germano et a., 1991; Moin et al, 1991)
  - MHD subgrid models (Balarac et al., 2010)
  - DNS+Hyperviscosity approach

Basic equations

The equations we solve are the grid-cell averaged

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + (\rho u_i)_{,i} = 0$$

Conservation of momentum:

$$\frac{\partial \rho u_i}{\partial t} + (\rho u_i u_j + P_{ij})_{,j} = -\rho \phi_{,i}$$

Conservation of energy:

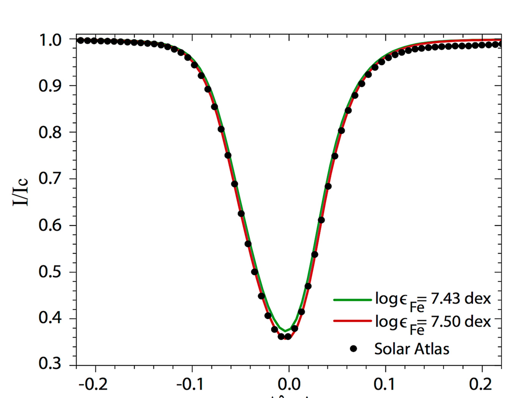
$$\frac{\partial E}{\partial t} + \begin{pmatrix} E u_i + P_{ij} u_j - \kappa T_{,i} + \\ + \left(\frac{c}{4\pi}\right)^2 \frac{1}{\sigma}(B_{i,j} - B_{j,i}) B_j + F_i^{\mathrm{rad}} \end{pmatrix}_{,i} = 0$$

with

$$P_{ij} = \left(p + \frac{2}{3}\mu u_{k,k} + \frac{1}{8\pi} B_k B_k\right)\delta_{ij} - \mu(u_{i,j} + u_{j,i}) - \frac{1}{4\pi} B_i B_j$$

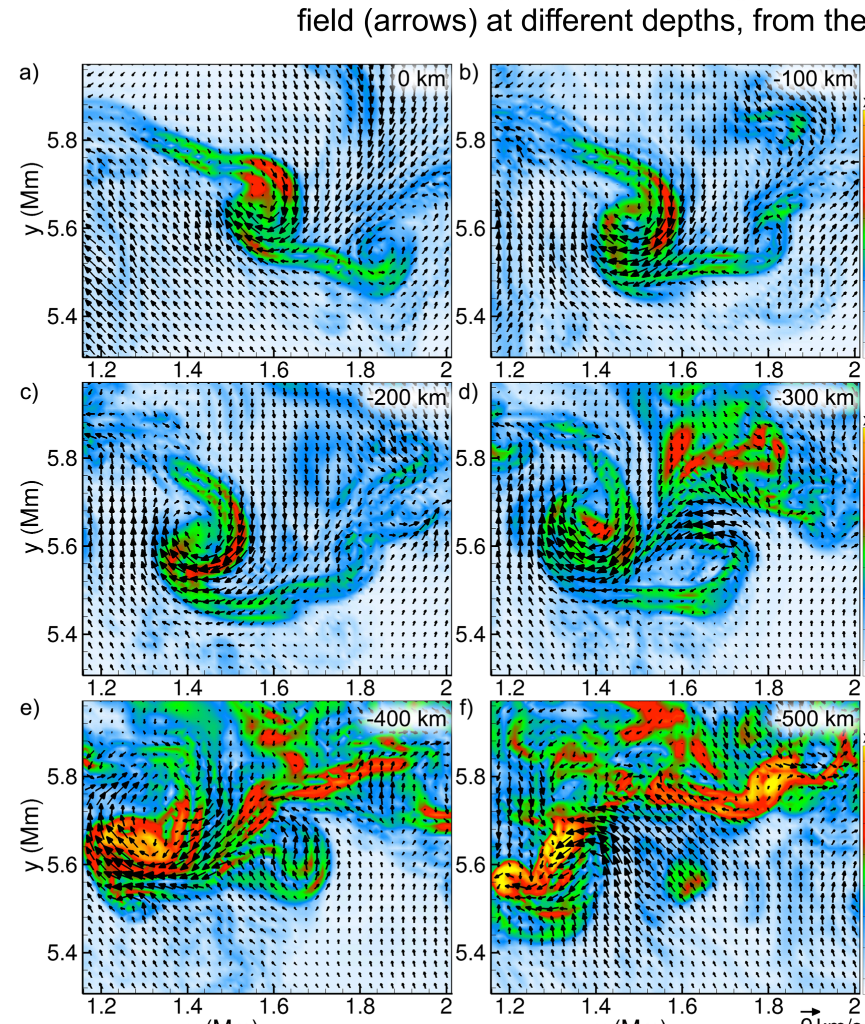
Conservation of magnetic flux

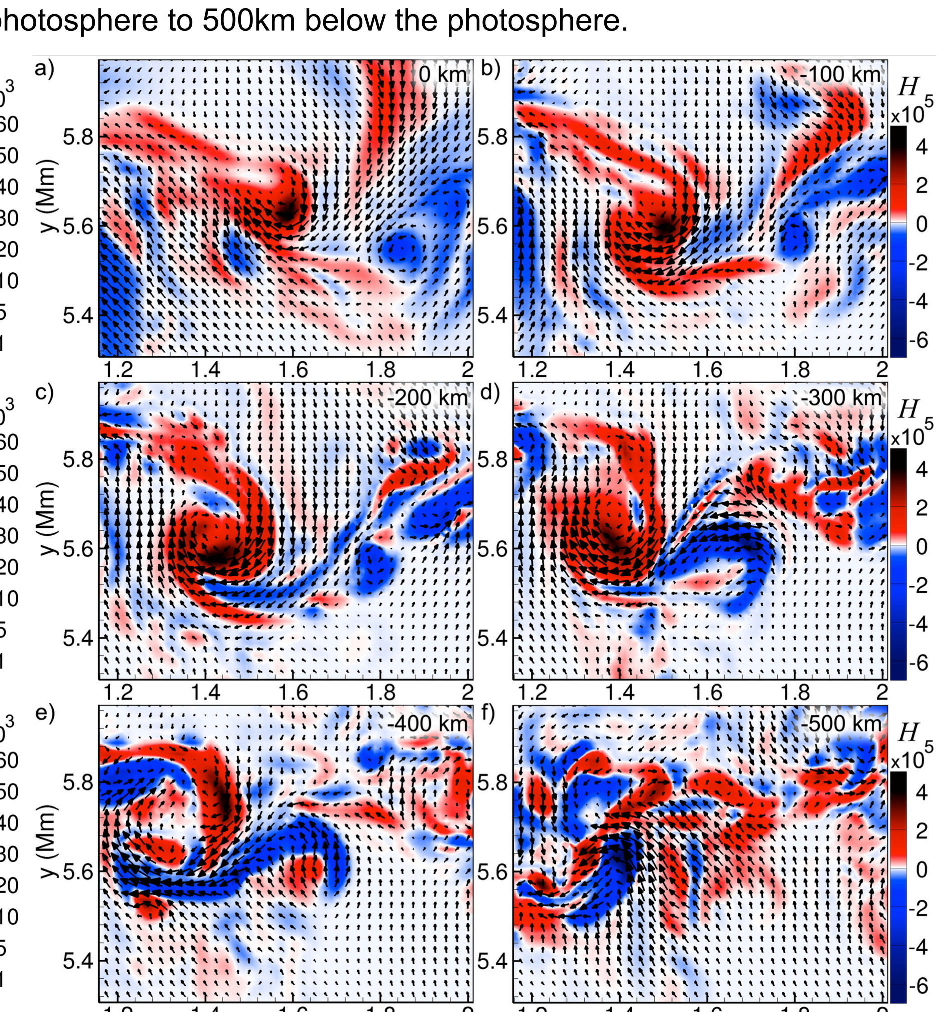
$$\frac{\partial B_i}{\partial t} + \left(u_j B_i - u_i B_j - \frac{c^2}{4\pi\sigma}(B_{i,j} - B_{j,i})\right)_{,j} = 0$$



Comparison of the synthetic line profiles obtained from our simulations for two iron abundances, and from observations with FTS for the line 6173 A.

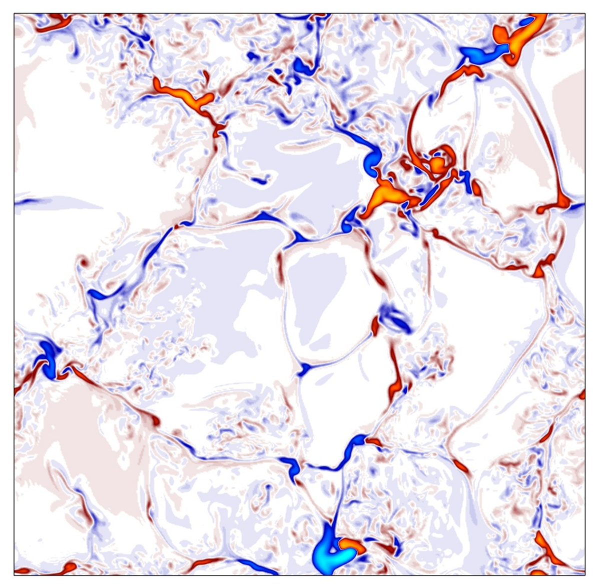
The electric current density (left, color background), the kinetic helicity density (right), and the horizontal velocity field (arrows) at different depths, from the photosphere to 500km below the photosphere.

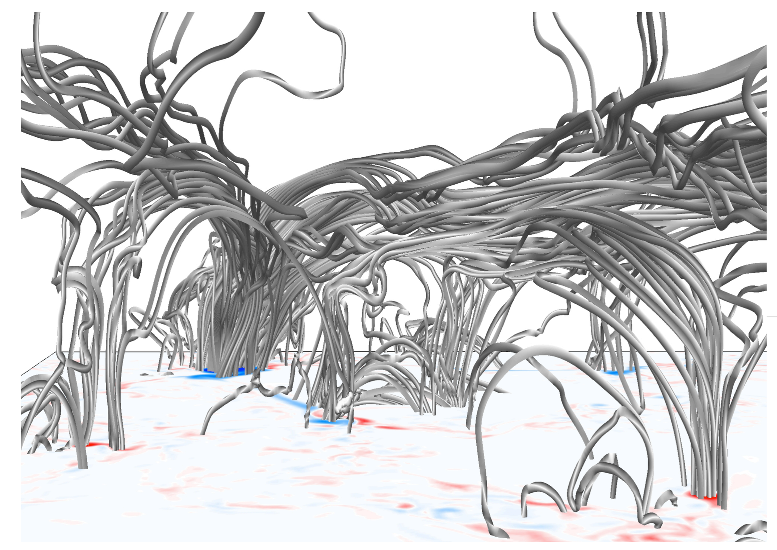




Local Dynamo

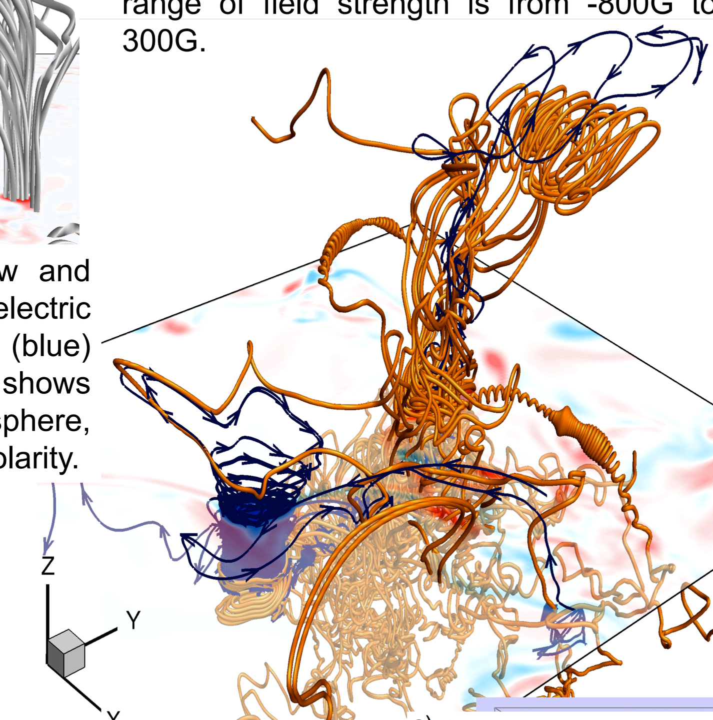
Formation of magnetic patches by turbulent dynamo action from an initial 10^{-6}G random seed field. The blue-red color scale corresponds to vertical magnetic field strength from -300 to 300 G at the photosphere layer. A typical size of the magnetic structures is 100 to 300 km.

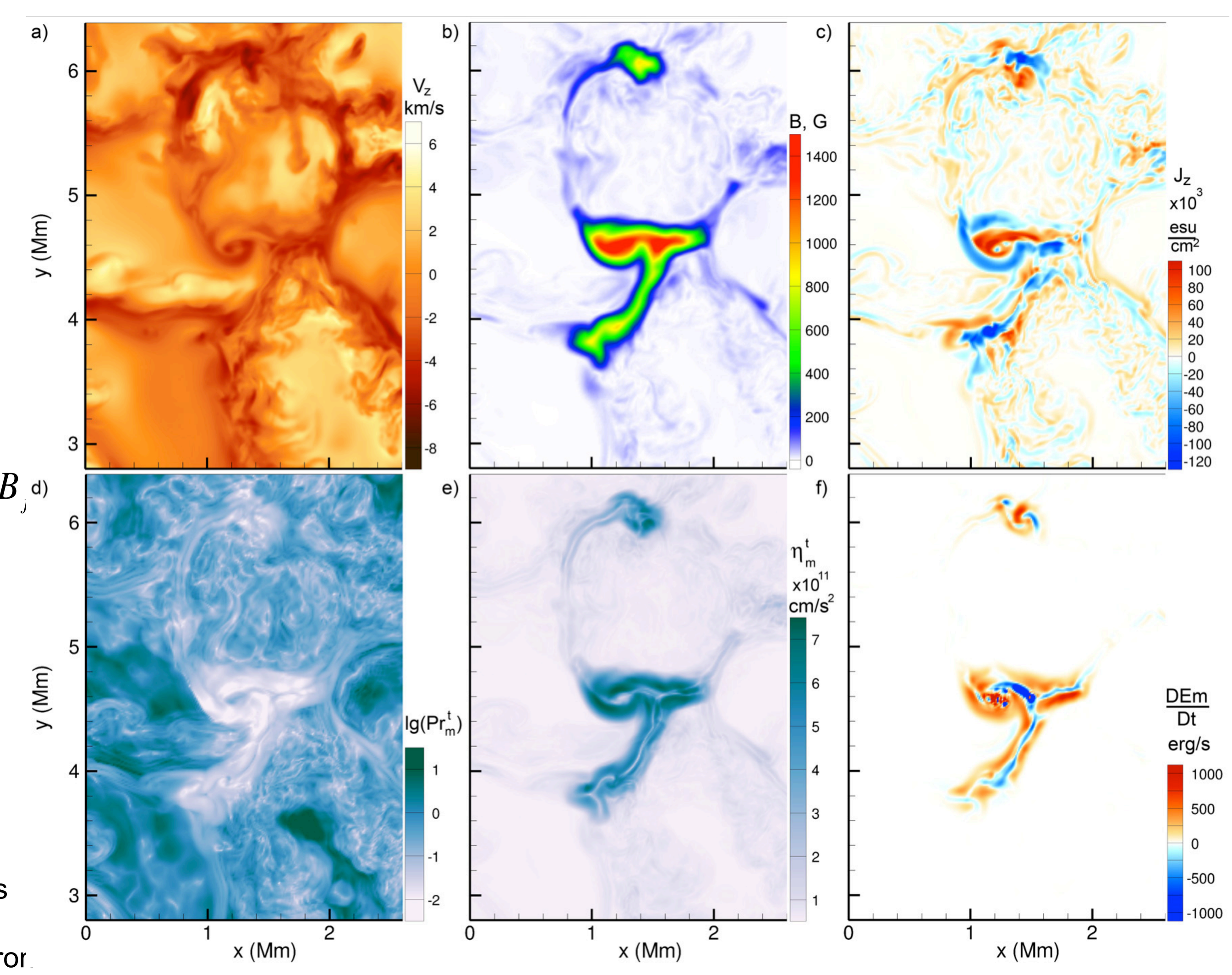




Topological structure of electric current density below and above the photosphere. Streamlines correspond to electric currents originating from positive (orange) and negative (blue) polarity patches. The semi-transparent horizontal plane shows the vertical magnetic field distribution in the photosphere, where blue indicates negative polarity and red positive polarity.

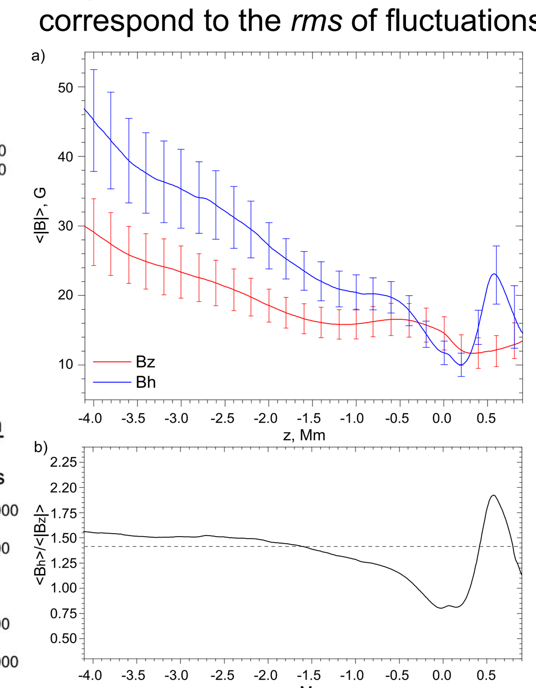
Topology of the magnetic field lines above the photosphere in the local dynamo simulations. The horizontal plane shows the distribution of the vertical magnetic field in the photosphere. Red corresponds to positive polarity and blue to negative polarity of the vertical magnetic field. The range of field strength is from -800G to 300G.





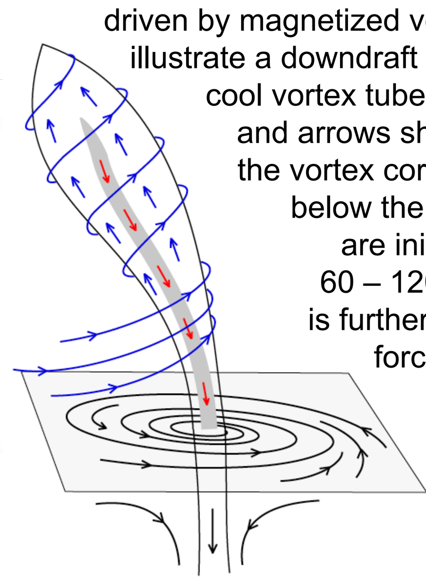
Horizontal snapshot of a section of the computational domain in the photosphere for: a) vertical velocity; b) magnetic field strength; c) vertical component of the electric current density; d) logarithm of the turbulent magnetic Prandtl number; e) turbulent magnetic diffusivity; and f) time-derivative of the magnetic energy density.

Mean vertical profiles of the unsigned magnetic field components. Error bars correspond to the *rms* of fluctuations.

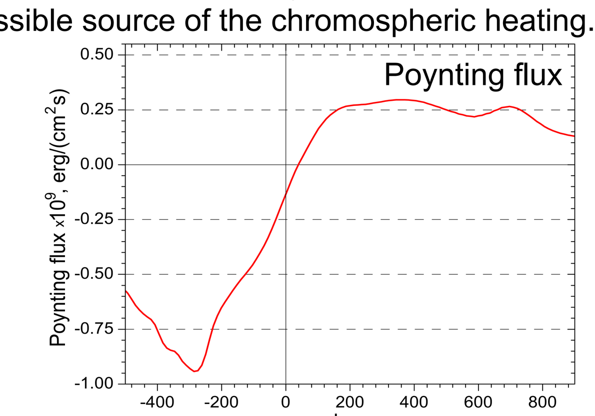


Ratio of the mean vertical and transverse components of magnetic field as a function of depth below the photosphere.

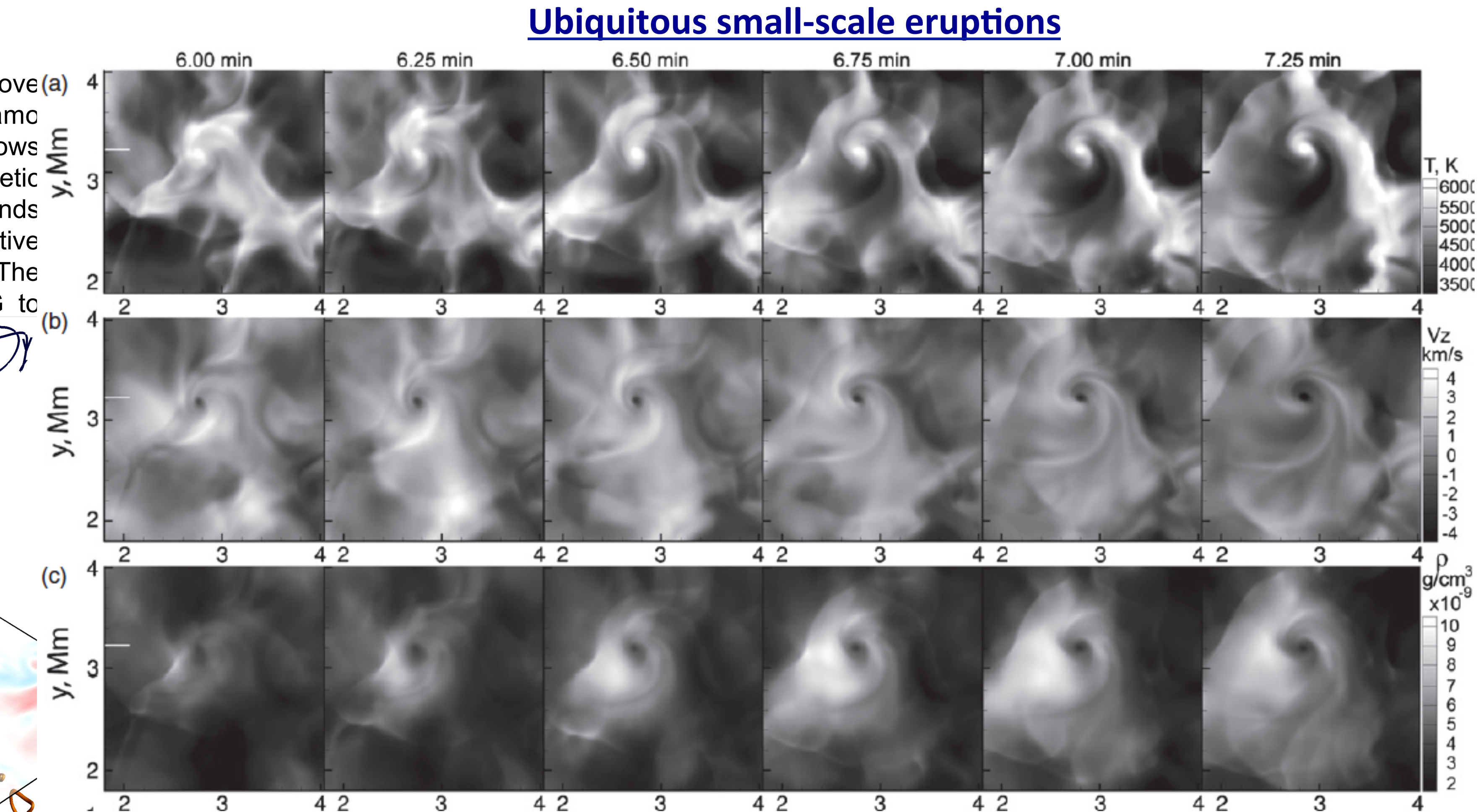
Schematic illustration of the flow pattern in eruptions driven by magnetized vortex tubes. The red arrows illustrate a downdraft in the low-density, relatively cool vortex tube core (gray area); blue lines and arrows show swirling upflows around the vortex core. The vortex tube is rooted below the surface, and flow eruptions are initiated by a pressure excess 60 – 120 km below the surface that is further accelerated by the Lorentz force in the mid-chromosphere.



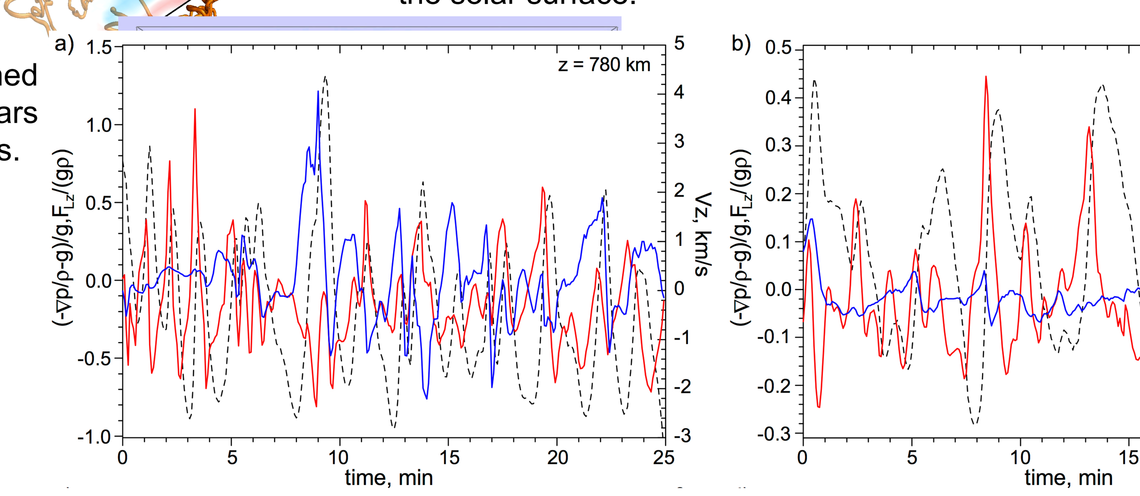
Mean vertical distribution of the Poynting flux shows that the local dynamo action can be one possible source of the chromospheric heating.



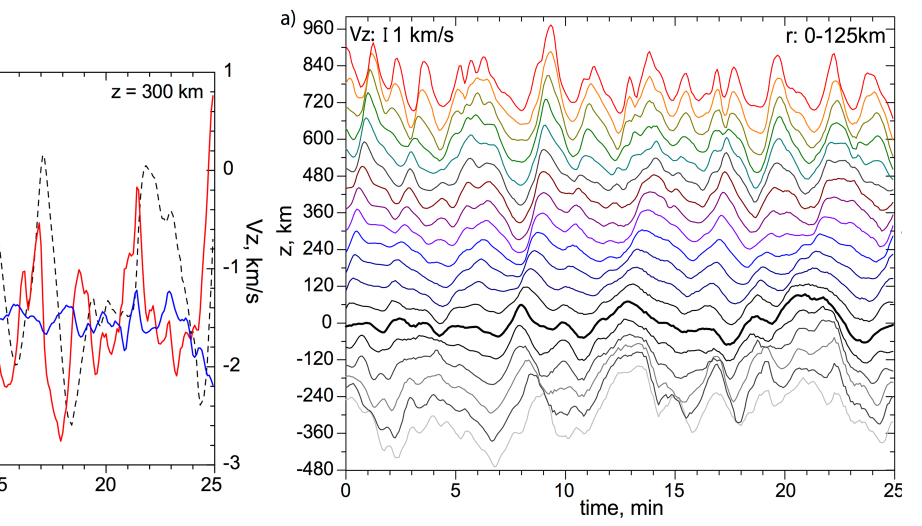
Ubiquitous small-scale eruptions



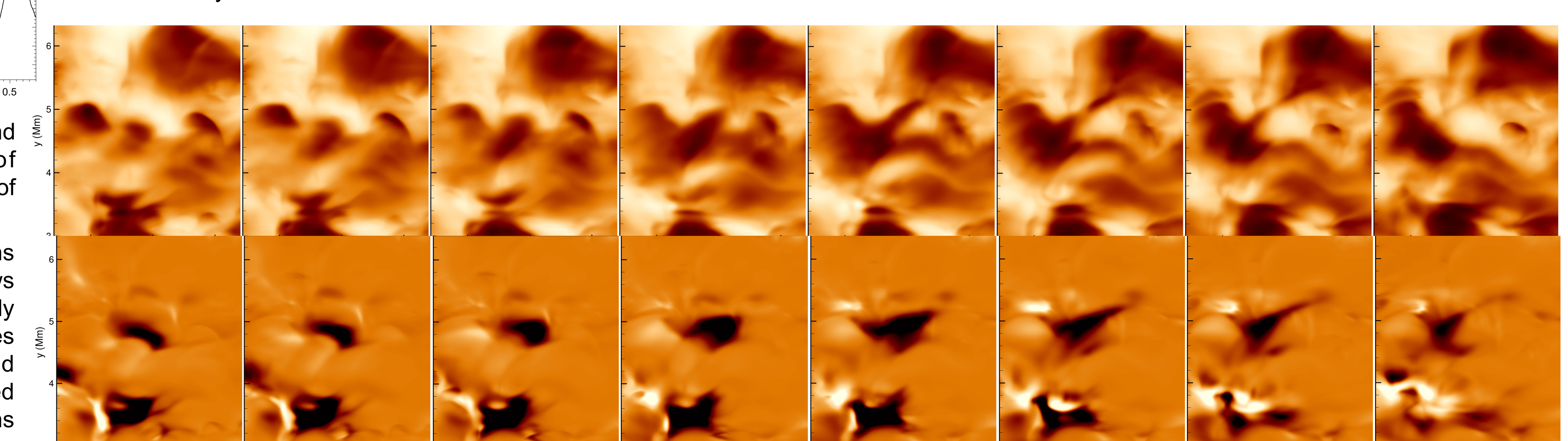
Time series with 15s cadence of of temperature (a), vertical velocity (b), and density (c) at a height of 625 km above the solar surface.



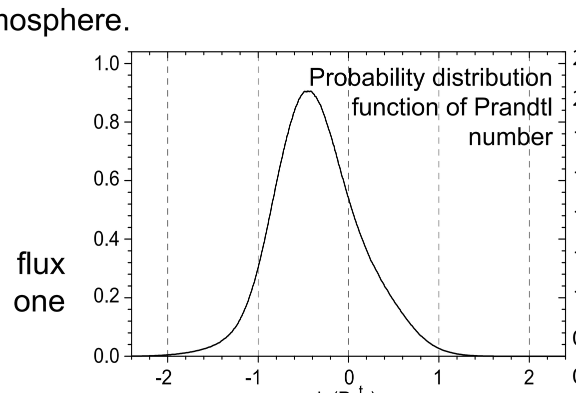
Comparison of contributions to flow ejection of hydrodynamic (red curves) and magnetic (Lorentz force, blue curves) vertical accelerations (normalized by the gravitational acceleration) at two altitudes: 780km & 300km above the photosphere. Dashed curves show the vertical velocity, V_z, given for reference at the same layers.

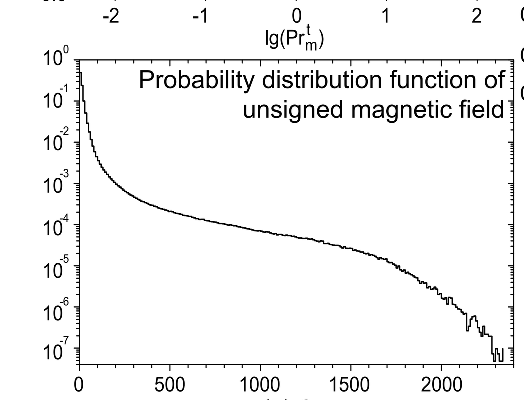


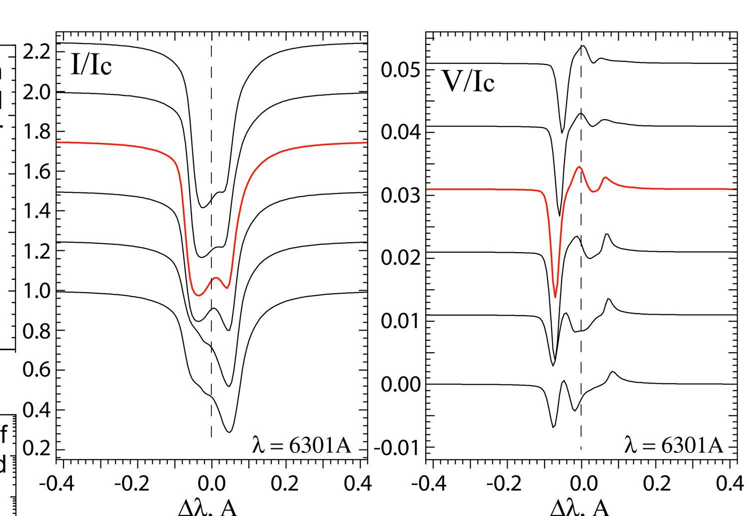
Temporal profiles of variations of the mean vertical velocity, V_z at different levels below the surface and in the atmosphere. The thick black curve shows the variations in the photosphere level. The height difference between the curves is 60 km.



Small-scale eruption signatures reflected in Stokes I and V. Panels (a) and (b) show zoomed images of I/Ic and V/Ic for $\Delta\lambda$=-0.06A (6301.5A). The time between snapshots is 10s.







Flow eruption reflected in Stokes I and V. Different panels illustrate the evolution of Stokes profiles I/Ic and V/Ic for 6301A. Red-line profiles correspond to the time and location marked by the circle above.

Conclusions

High-resolution observations reveal intense and dynamic interactions between the surface layers and the low atmosphere in quiet-Sun regions with relatively weak mean magnetic field. Radiative MHD simulations can reproduce many features of the observed phenomena and provide an important complimentary tool for investigation of the underlying physical processes. According to our numerical simulations the local dynamo process is responsible for the quiet-Sun magnetic field. It operates in the near-surface layers and provides Poynting flux sufficient to heat the chromosphere and corona. Spontaneous and ubiquitous flow eruptions occur everywhere in the quiet Sun. These eruptions are driven by impulsive increases in pressure gradient due to turbulent motions associated with vortex tubes. The plasma flow in the eruptions is accelerated by the Lorentz force in higher (mid-chromospheric) layers from 6 to 12−15 km/s. Our simulations demonstrate that shock generation in the chromosphere can be due to spontaneous vortex tube dynamics.